# Preliminary design and testing of the laboratory system to measure rotor blade deflections
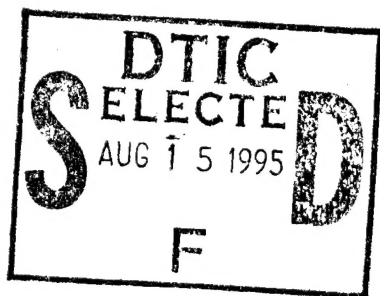
## Final Technical Report

by

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## CENTRAL AEROHYDRODYNAMIC INSTITUTE TsAGI

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# Preliminary design and testing of the laboratory system to measure rotor blade deflections.

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## *Abstract*

Research programs conducted in the National Full-Scale Aerodynamics Complex (NASA, Ames) requires a non-invasive instrumentation capability to measure the dynamic deflection of large scale rotor blades during wind tunnel test. TsAGI suggests to design, develop and test of a prototype measurement system, including mast mounted two dimensional coordinate sensor, a set of the retroreflectors installed on the blade, digital image acquisition and processing system coupled with a personal computer, synchronizing and power supply units. Measurement methodology and appropriate software must be developed and tested. This paper describes results obtained during Preliminary stage of this project, what is aimed to evaluate the possibility of the measurements, to approve required measurement accuracy, to develop measurement methodology and to formulate the technical requirements to the prototype system. All investigations were carried out on the laboratory measurement system simulating real geometry. Test results using real data are described, analyzed and compared.

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*List of Keywords*:

- Helicopter Rotor Blade
- Optical Measurements
- Deformation Measurements
- Machine vision

## *Table of Contest*

## Introduction.

An extremely difficult problem of current interest is the non contact determination of geometrical parameters of objects' surfaces such, for example, as surfaces of various elements of flight vehicles, machine structures, as well as determination of shape, position, movement and deformation of such surfaces.

Rotating helicopter's blade undergoes complex non stationary aerodynamic and inertial loads. In this process blade completes spatial movement, suffers bending and torsion deformations what change its aerodynamic performance. To determine by CFD methods all aspects of motion and deformation in diverse of flight regimes is not possible. What is why the problem of the direct measurements is actual up to day.

Known in the art is a great number of non contact optical methods and devices based on holographic, moiré and light interference principles designed to meet specific requirements relating to the above problem.

In the beginning of eighties TsAGI paid a lot of attention to the development and experimental investigation of the optical systems for non contact measurements of the rotor blade trajectory and deformations. All these projects were based on the interference differential method [1-2] and its derivatives [4,6,7]. Three prototype systems were designed and tested in the wind tunnel environments. Technical solutions were patented in the United States, France, Germany [4,5,7, 11,13,14] and Russia [6, 8, 9, 12].

In the end of eighties Laser Scanning System was designed and put in the practice for large scale blade investigations. This system was based on time interval measurements while scanning of the retroreflectors installed on the blade by a laser beam. The main difficulties encountered in experimental application of the laser measurement system were due to mechanical stability of the optical scanner and high sensitivity to the experimental environments. System was used mainly in T-101 wind tunnel. Typical results obtained in T-101 wind tunnel and showing data spread, are presented on Fig. I1.
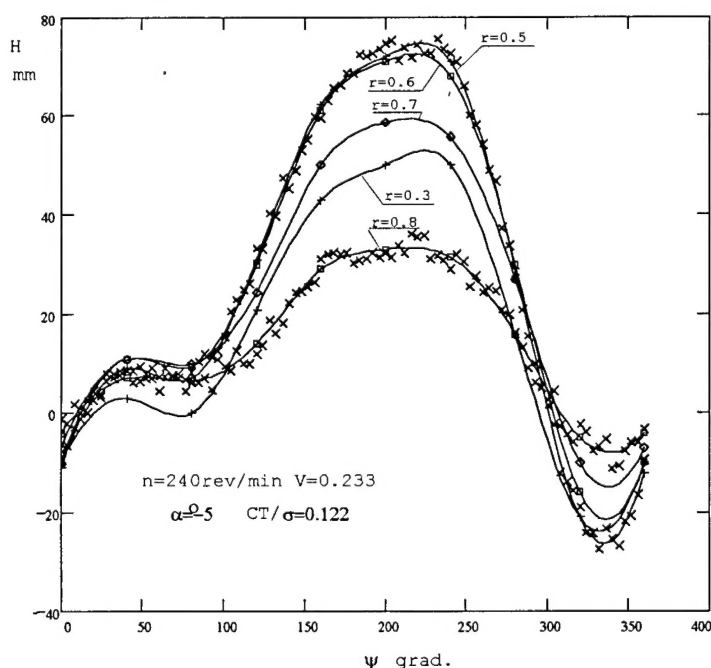


Fig. I1. Bending of the rotor blade for stations
r=0.3, 0.5, 0.6, 0.7, 08
(solid lines--data approximation, ×-experimental results for r=0.5 and r=0.8)

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Meanwhile we concentrated our efforts on spatial coordinates' measurements by a solid state CCD array. Achievements in solid state matrix photo detector give the possibility to create more accurate and versatile tool for spatial coordinate measurements. Comparatively high spatial resolution (about 4000*4000 units) of the suggested optical measurement system is based on the so-called sub pixel resolution of a CCD TV camera [3]. The retroreflectors, placed on the blade under study and illuminated with flash lamp, can be detected by CCD array and their coordinates can be measured after digital processing of the video signal. Time resolution is determined by flash duration and is about 0.05-0.1 msec. Acquisition rate is proportional to the frame rate of the TV camera.

This problem is encountered in our recent research while using of a pressure sensitive paint technology. Experimental results obtained in wind tunnel tests [14-16] gave promising results but showed that additional efforts must be applied in order to reach such resolution in experimental environment.

# 1.   Feasibility investigations

The prototype of the measurement system under development is aimed to study full scale (diameter about 13 m) helicopter rotor in the wind tunnel environment. In the laboratory experimental setup we tried to reproduce actual geometry or at least to simulate geometry where it is possible.
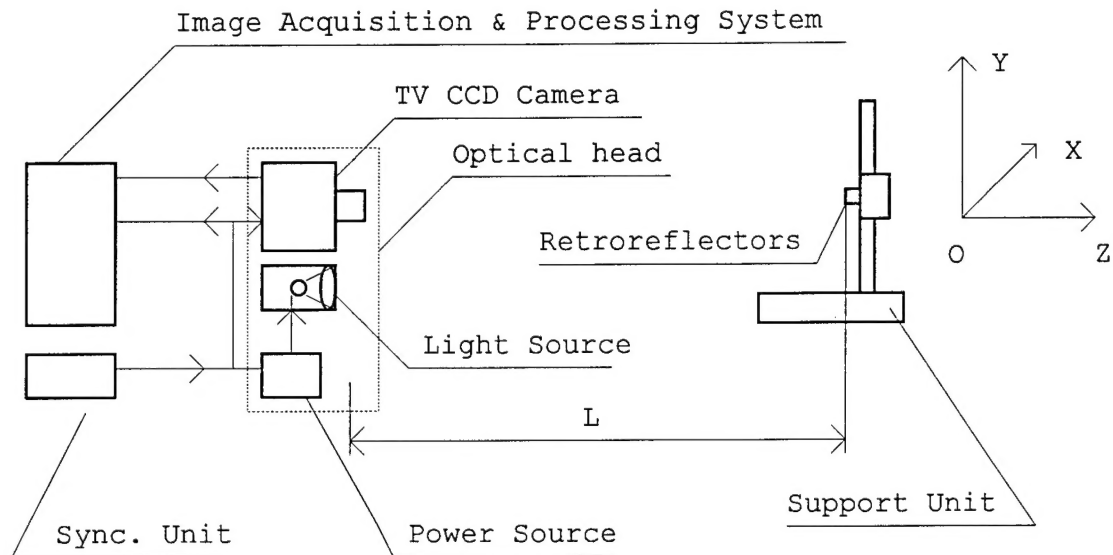
*Experimental setup.*

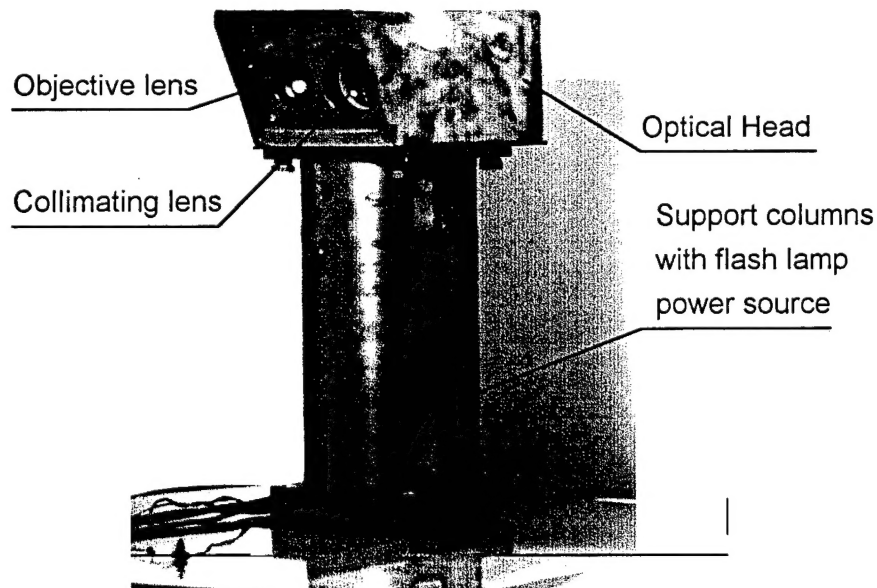Fig. 1.1a. General Layout of the laboratory System

Fig. 1.1b. Optical head developed for laboratory tests.

The general layout of the measurement system is presented on Fig. 1.1a. CCD camera "Monacor TVCCD-2006" with the light source was installed on common base-optical head presented on Fig. 1b. Retroreflectors were placed on the support unit of the two types:

a. having possibility to install and to measure linear displacement in vertical or horizontal direction;
b. having possibility to install and to measure angular displacement.

Specification of the CCD camera:

| | |
|---|---|
| Image sensor | :1/2" CCD chip (6.47*4.85 mm) |
| Synchronization | :hor. 15.625 kHz/vert. 50 Hz |
| Pixels | :hor. 795, vert. 596 |
| Bandwidth | :5.8 MHz, -6dB |
| Min. Illumination | :0.02 LUX/-6dB |
| S/N Ratio | :>48 dB/5 lux |
| Electronic Shutter | :1/10000-1/125 sec |
| Operational temperature | :-5 up to +45$^O$C |
| Dimensions | :W 42 x H 62 x D 110 mm |
| | (without lens and connectors) |
| Weight | :330 g |

In order to cover conical deflection angle b=-5$^O$ to +10$^O$ and to obtain maximum spatial resolution the focal lenght f=16 mm and height h=450 mm of the camera position relative rotation plane were choosen. Geometrical scheme of the prototype system is shown on Fig.1.2. Camera viewing angle in the vertical direction $2\alpha_x$=0.168=22.4$^O$, and in the horisontal direction

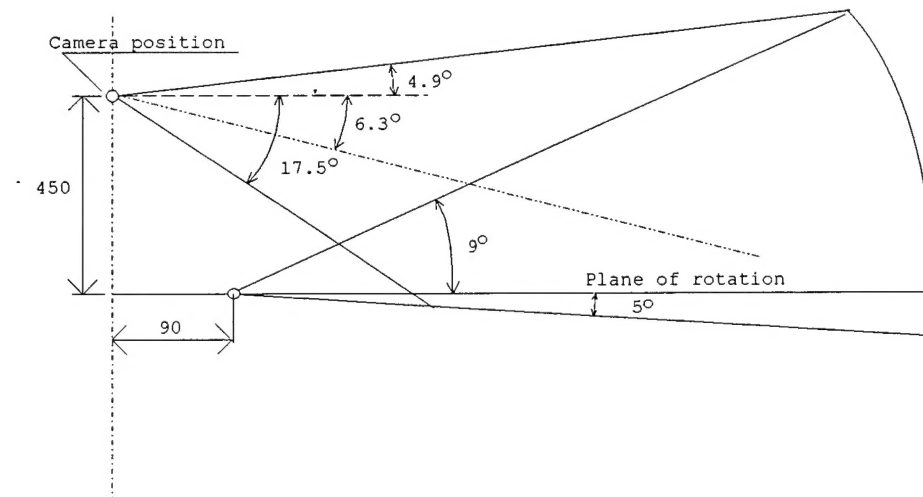$2\alpha_y$=0.150=17.1$^O$. Angular resolution $\Delta\alpha$=0.505$_{10}$-3 are the same in both direction.



Fig.1.2. Geometry of a prototype system.

This configuration provides the measurements of the conical deflection angle b=-5°-+9° in sections r=0.3-1.0 and b=-2.3°-9°in section r=0.25-1.00. The angle between optical axes of the CCD camera and the rotation plane is -6.3°.

Spatial resolution $\Delta_x$ is estimated in Table 1 (L-distance from the camera)

Table 1.

| L, m | 1.5 | 2 | 2.5 | 3 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 |
|------|-----|---|-----|---|-----|-----|-----|-----|-----|-----|-----|
| $\Delta_x$, mm | 0.76 | 1.01 | 1.27 | 1.52 | 1.77 | 2.03 | 2.28 | 2.54 | 2.79 | 3.04 | 3.30 |
| D, mm | 2 | | 3 | | 4 | | 5 | | 6 | | |

D-is the recommended diameter of the retro reflector that is chosen to be equaled two units of the spatial resolution.

Objective lens focusing must provide contrast imaging of the retroreflectors placed on the boundaries distances r=0.25 and r=1. D-input optical diameter of the objective lens and L-sharpness distance are tuning parameters. If image defocusing on the boundaries r=0.25 (162.5mm) and r=1 (6500 mm) doesn't increase multiplied by two spatial resolution then D<4.4 mm, and L=2.6 m.

## *Retroreflectors.*

As mentioned above retroreflector type and its geometry have to be optimized. Two schemes of the retroreflectors were suggested and tested.

a. Retroreflector is a round piece of special retroreflectors film widely used in manufacturing of the road signs and cinema screens. The scattering diagram of this film has sharp pulse in the direction of the incident light. Retroreflectors are glued to the surface of crest attached to the blade surface as shown on Fig. 1.3.
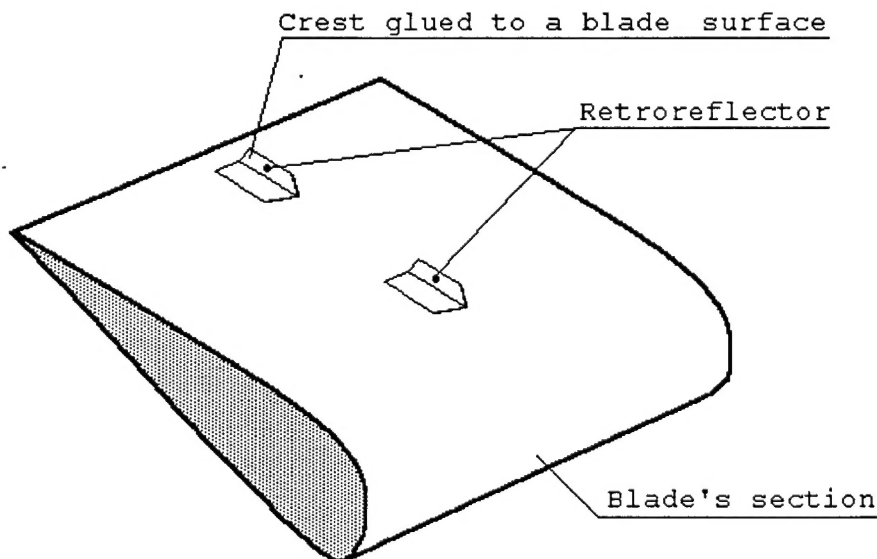


Fig. 1.3 Retroreflector placing on the blade section.

b. Retroreflector is the narrow band of the luminescent layer applied directly to the blade surface in the appropriate cross sections. The last scheme less effective in the output signal level, but

more promising from the point of view of flow distortion and mechanical stability. This scheme was used in wind tunnel tests while measurements of a wing deformation (see below).

## Laboratory acquisition system.

Standard video signal from CCD camera was acquired by digital image processing system PC3000.

Specification of the PC3000 system

| Maximum spatial resolution | :720 pixel*512 lines |
|---|---|
| Amplitude resolution | :256 gray levels |
| Acquisition rate | :25 frames/sec |
| Image RAM | :12Mbyte (40 images with resolution 512*512 pixel) |

Really acquisition rate of the PC3000 is 50 half interlaced frames per second (256 lines in each half frame). External synchronizing unit was developed to synchronize CCD camera, PC3000 system and flash lamp. CCD camera is equipped with electronic shutter having expose time up to 1/10000 sec. that in combination with flash lamp sharply increase the contrast of the image.

## Coordinate determination.

### Algorithm.

Due to abundance of the information in two dimensional intensity distribution in the image of the retroreflector it is possible to determine the coordinates of some invariant with accuracy exceeding the spatial resolution of the image acquisition system. "Mass" center or distribution extremum can be used as such invariants. At least two requirements must be satisfied:

a. image of the retroreflector occupied some pixel region-usually from 3*3 up to 7*7 pixel;
b. image intensity distribution doesn't change while image displaces in image plane.
Typical intensity distribution in the retroreflector image is presented on Fig. 1.4.
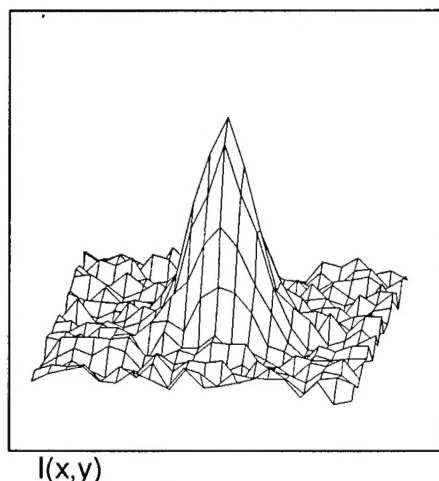


$I(x,y)$

Fig. 1.4. Intensity distribution in the retroreflector image.
Window ($11\times11$ pixel) is centered on the maximum intensity.

Spatial resolution in this case can be increased in five - ten times, this is so-called super resolution approach. Thus, having system with 512*512 pixel resolution it is possible to create measurement system with spatial resolution up to 4000*4000 units.

"Mass" center invariant was used in realized versions of the software. The coordinates of the "mass" center are determined by next formulas:

$$x_c = \frac{\sum\limits_{|i-I|\leq M,|j-J|\leq N} U_{ij} X_{ij} H(U_{ij} - U_{th})}{\sum\limits_{|i-I|\leq M,|j-J|\leq N} U_{ij} H(U_{ij} - U_{th})} ; y_c = \frac{\sum\limits_{|i-I|\leq M,|j-J|\leq N} U_{ij} Y_{ij} H(U_{ij} - U_{th})}{\sum\limits_{|i-I|\leq M,|j-J|\leq N} U_{ij} H(U_{ij} - U_{th})} ,$$

where: $U_{ij}$-signal amplitude in the point with coordinate (i,j), $U_{th}$-some threshold value of signal, H- Haviside function, and coordinates are determined in window (2*M+1)*(2*N+1) pixels with center coordinates (I,J). A threshold value is chosen above image background value. Coordinates $(x_c, y_c)$ are independent from window position if window's dimensions and threshold value are correctly chosen.
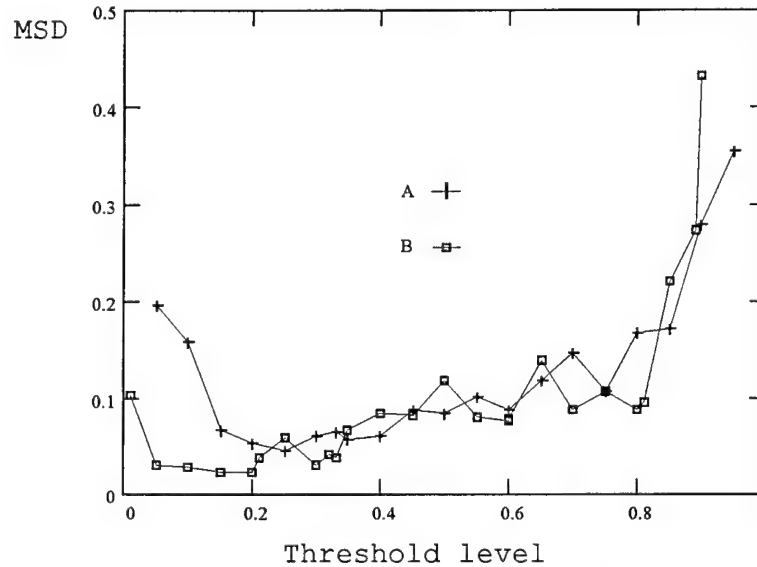


Fig. 1.5 Estimation for mean square deviation in "mass centrum" measurements as function for threshold level (A - SNR=40Db, B-26Db)

Plot on Fig. 1.5 shows estimations of the measument error (mean square deviation) as function of threshold value obtained for SNR=40 Db (A) and SNR=26 Db (B) in the digitized signal. Optimum threshold value varies from 0.2 to 0.8 from maximum signal level.

### Program.

The program is written on PLM86 language in MTR286 operational system and integrated in standard software of PC3000 machine. Before starting of the coordinate determination procedure operator must choose appropriate markers and after that program automatically tracks position of these markers and saves their coordinates in data file. In this mode program is able to track up to 4 markers. Threshold level for each marker is determined automatically -30% of maximum intensity in marker image.

## Results of the measurement.

As mentioned above measurement accuracy was investigated in the laboratory environment simulating real geometry.

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Test program included measurements of the retroreflector's coordinates placed at known positions or displaced at known distances along TV line (X axes), perpendicular to TV line (Y axes) and rotated about viewing axes ($\alpha$ angle).

Linear coordinates were installed in the range 0-500 mm with step 20 mm and accuracy 0.1mm.

Tilting angle was determined by the formula from increments $\Delta y$, $\Delta x$ in positions of two retroreflectors:

$$= arctg\left(\frac{\Delta y}{\Delta x}\right).$$

Retroreflectors were placed on a bur attached to a limb having nonius with resolution 0.05 degree. In these tests two pairs of retroreflectors were used. Distances between them were 140 and 330 mm (Fig. 1.6).



Fig. 1.6 Tilting Support Unit.
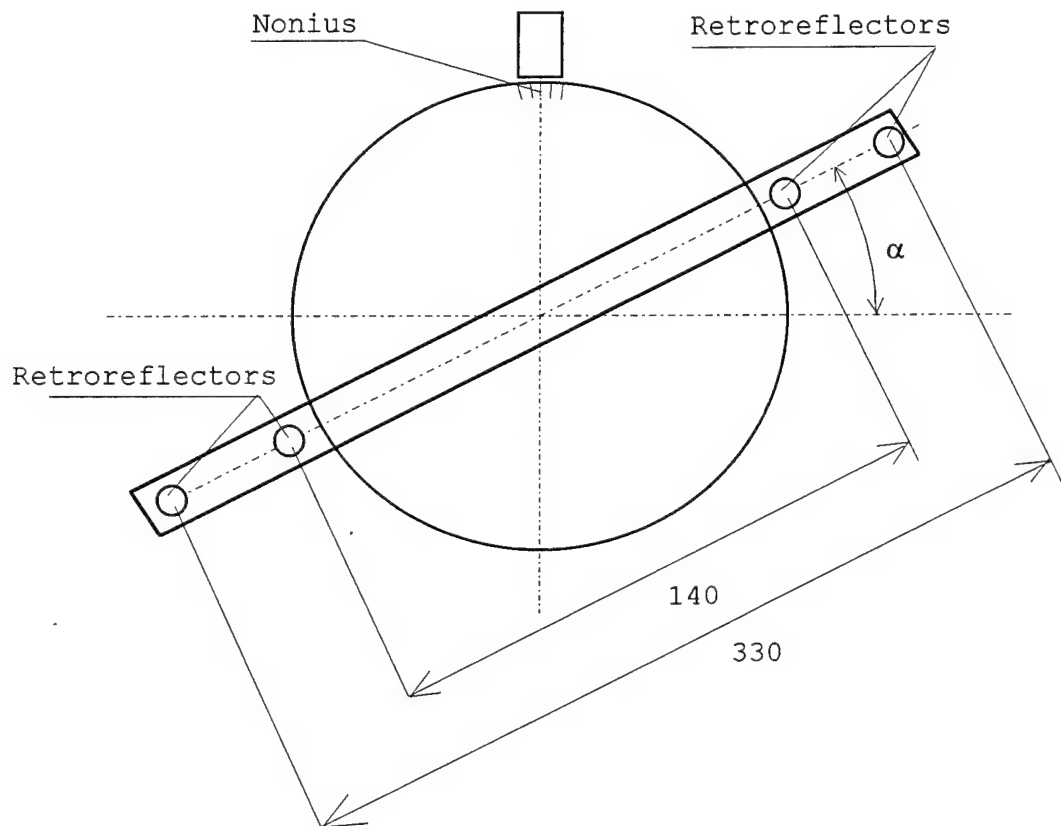
In addition to vector's module

$$m = \sqrt{(\Delta x^2 + \Delta y^2)}$$

was determined and compared with known distance between retroreflectors.

Investigations of the measurement accuracy were performed at two distances from CCD camera L=4 and 8 m. In all cases retroreflectors with diameter d=5mm were used..

Measurement results were approximated by linear equations:

x'=aX+b and y'=aY+b,

where a-image scale. On the plots (Fig. 1.7) discrepancy of measured and installed coordinates in x direction are presented:

$$dx=aX+b-x,$$

and the same for y direction on the plots on Fig. 1.8)

The values of the scale coefficients a, offsets b and mean squared deviation (MSD) are presented on plot's header.

Measurements shown the small difference image scales in x and y directions:

$a_x/a_y \cong 1.01$. In addition to a values characterize spatial resolution what is 0.8 mm for distance L=4m and 1.6 mm for distance L=8m.

MSD is in the range 0.2-0.5 pixel. Influence of the distance L on MSD didn't appear what may be due to large diameter of retroreflector in comparison with spatial resolution: for L=4 m d/a=6, and for L=8m d/a=3. The measurement error is mainly determined by retroreflector diameter.
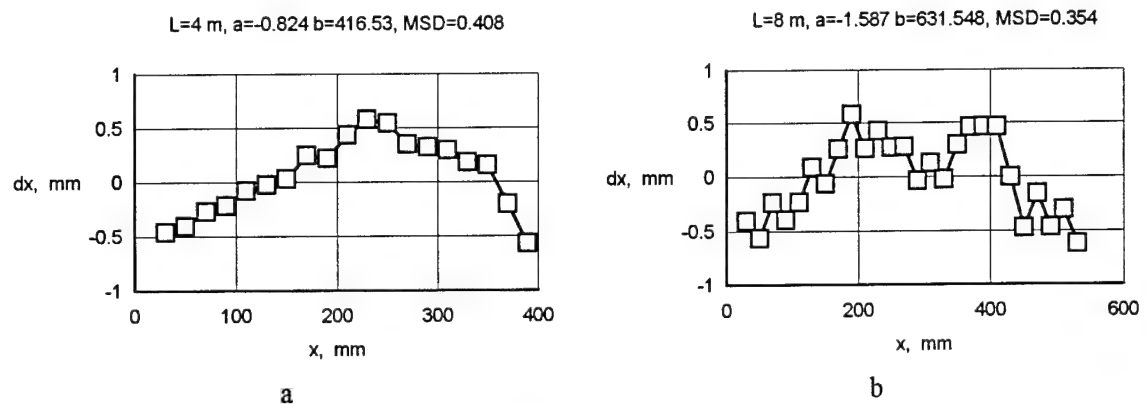


Fig. 1.7. Discrepancy Plot for x direction.
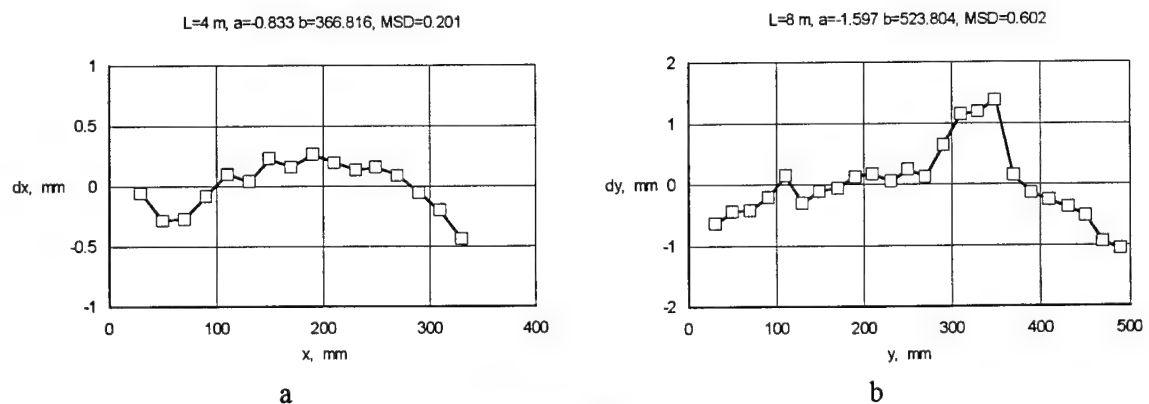
    a)  distance L=4m
    b)  distance L=8m



Fig. 1.8. Discrepancy Plot for y direction.

    a)  distance L=4m
    b)  distance L=8m

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It is possible to make conclusion that retroreflector diameter must be in the range 1-3 of resolution unit.

The results of the tilting angle measurements for L=4m are presented on Fig. 1.11 and for L=8m - on Fig. 1.13. The curves with label 1 correspond to base distance B=330 mm, and with label 2 -- B=140 mm. Angle measurement error is proportional to distance L (MSD=0.035 rad or 0.07°), that really takes place if coordinate measurement error is constant.

The results of comparisons of B values with measured distance between retroreflectors are shown on Fig. 1.12 (L = 4m) and on Fig. 1.14 (L = 8m). Distance between points is measured more precisely then absolute coordinate value.

Comparisons of the results obtained in two a- measurement series (Fig. 1.9 and Fig. 1.11) demonstrate what repeatability is well enough.

L=4 m, MSD1=0.024, MSD2=0.038
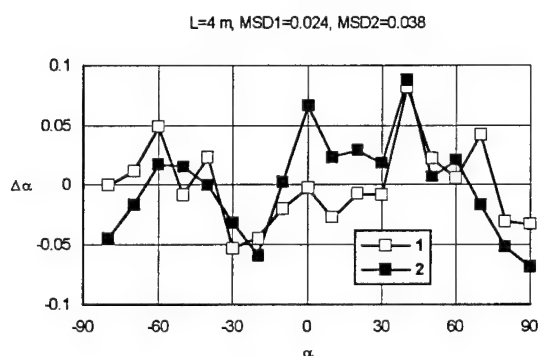
Fig. 1.9 Spread in tilting angle measurements for L = 4m

L=4 m, MSD1=0.081, MSD2=0.080
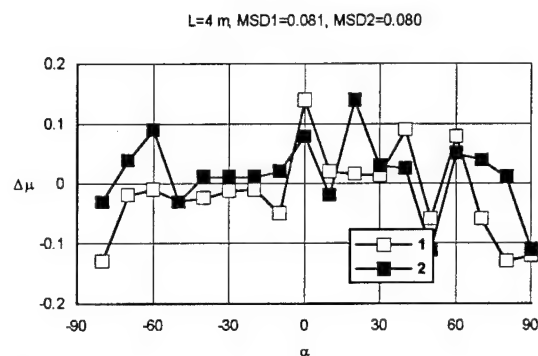
Fig. 1.10 Spread in base measurements for L = 4m

L=4 m, MSD1=0.03, MSD2=0.034

Fig. 1.11 Spread in tilting angle measurements for L = 4m

L=4 m, MSD1=0.083, MSD2=0.067
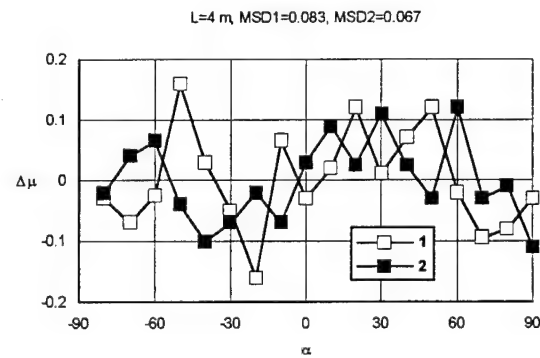
Fig. 1.12 Spread in base measurements for L = 4m

□-base distance 330 mm, ■--base distance 140 mm

L=8 m, MSD1=0.023, MSD2=0.07

L=8 m, MSD1=0.247, MSD2=0.179
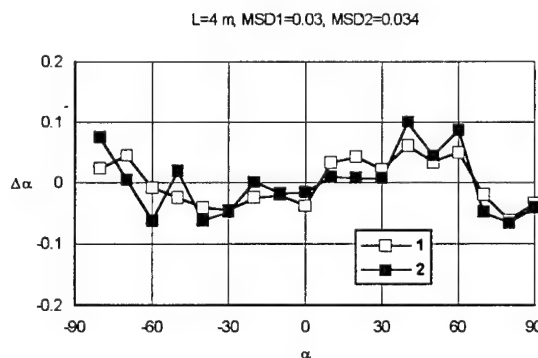
Fig. 1.13 Spread in tilting angle measurements for L = 8m
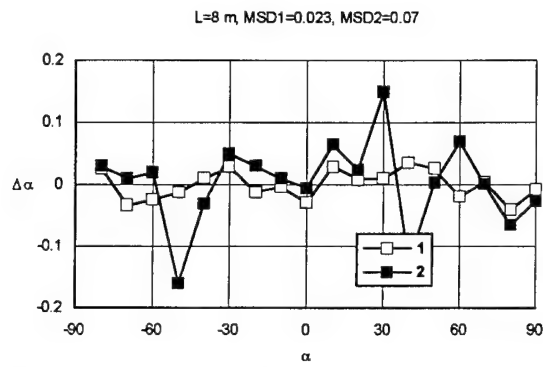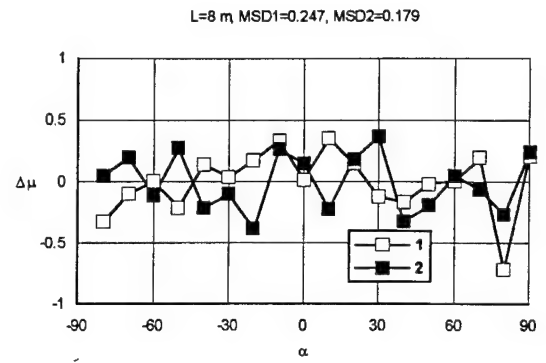
Fig. 1.14 Spread in base measurements for L = 8m

□-base distance 330 mm, ■-base distance 140 mm

# 2. Measurement System Identification

## Camera Calibration Technique.

Camera calibration is the process of determining the internal camera geometric and optical characteristics (intrinsic parameters) and the 3D position and orientation of the camera frame relative to a certain coordinate system (extrinsic parameters).

The underlying camera model and the definition of the parameters to be calibrated will be used.

Fig. 2.1 illustrates the basic geometry of the camera model. $(x_h, y_h, z_h)$ is the 3D coordinate of he object point P in the 3D coordinate system attached to the hub in our case. Let center camera coordinate system at point O, the optical center, with the z axis the same as optical axis. $(X, Y)$ is the image coordinate system centered at $O_1$ (intersection of the optical axis z and front image plane) and parallel to x and y axes. $f$ is the distance between front image plane and the optical center. $(X_u, Y_u)$ is the image coordinate of $(x, y, z)$ if a perfect pin hole camera model is used. $(X_d, Y_d)$ is the actual image coordinate taking into account lens distortion. $(X_f, Y_f)$ is the same coordinates expressed in pixel values after frame digitizing.
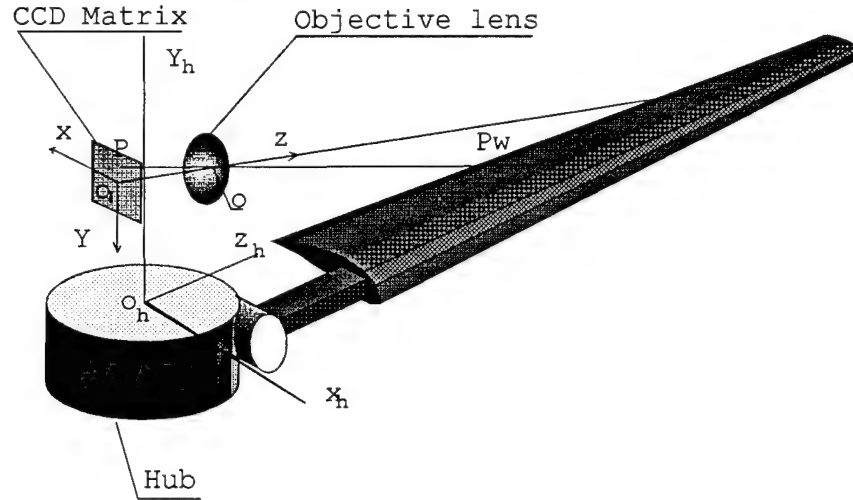


Fig. 2.1. Coordinate system and camera geometry.

Rigid body transformation from the hub coordinate system to the camera coordinate system:

$$((x,y,z)^T = R(x_h, y_h, z_h)^T + T^T \tag{2.1}$$

where $R$ is rotation matrix

$$R = \begin{bmatrix} r_1 & r_2 & r_3 \\ r_4 & r_5 & r_6 \\ r_7 & r_8 & r_9 \end{bmatrix} \tag{2.2}$$

$T$ is translation vector $\quad T \equiv (T_x, T_y, T_z) \quad$. Parameters to be calibrated: $R$ and $T$.
Perspective projection for pin hole model gives:

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$$X_u = f\frac{x}{z}$$

$$Y_u = f\frac{y}{z}$$

(2.3)

Parameter to be calibrated is effective focal length $f$.
Radial lens distortion can be described by equations:

$$X_d(1 + k_2 r^2 + k_4 r^4) = X_u$$
$$Y_d(1 + k_2 r^2 + k_4 r^4) = Y_u$$

(2.4)

where $r = \sqrt{X_d^2 + Y_d^2}$

Parameters to be calibrated: distortion coefficients $k_2$ and $k_4$.

Consideration is restricted be radial lens distortion which gives the main input in the image deformation.

Computer image coordinates $(X_f, Y_f)$ are transformed to real image coordinate:

$$X_f = s_x\frac{X_d}{d_x} + C_x$$

$$Y_f = \frac{Y_d}{d_y} + C_y$$

(2.5)

where $(C_x, C_y)$- computer image coordinate for the point $O_1$, $d_x, d_y$-actual pixel-pixel distances in x and y directions, $s_x$-some scale coefficient for TV camera having analog output. Parameters to be calibrated: uncertainty image factor $s_x$, image origin $(C_x, C_y)$.

The $(X, Y)$ computer coordinate is related to $(x,y,z)$, the 3D coordinate of the object point in camera coordinate system, by the following equation:

$$\frac{d_x}{s_x}X(1 + k_2 r^2 + k_4 r^4) = f\frac{x}{z}$$

$$d_y Y(1 + k_2 r^2 + k_4 r^4) = f\frac{y}{z}$$

(2.6)

where

$X = X_f - C_x$, $Y = Y_f - C_y$

$$r = \sqrt{(d_x s_x^{-1} X)^2 + (d_y Y)^2}$$

Substituting (2.1) into (2.6) gives:

$$\frac{d_x}{s_x}X(1 + k_2 r^2 + k_4 r^4) = f\frac{r_1 x_h + r_2 y_h + r_3 z_h + T_x}{r_7 x_h + r_8 y_h + r_9 z_h + T_z}$$

$$d_y Y(1 + k_2 r^2 + k_4 r^4) = f\frac{r_4 x_h + r_5 y_h + r_6 z_h + T_y}{r_7 x_h + r_8 y_h + r_9 z_h + T_z}$$

(2.7)

## Calibration definition

The problem of system calibration is to determine the system intrinsic and extrinsic parameters based on a number of points whose object coordinates in the $(x_h, y_h, z_h)$ are known, and whose

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image coordinate (X,Y) are measured. The parameters to be computed can be categorized into the following two classes:

### Extrinsic Parameters

The are six extrinsic parameters: the Euler angles yaw $\theta$, pitch $\phi$ and tilt $\psi$ for rotation, the three components for translation vector $T$. The rotation matrix $R$ can expressed as follows:

$$R = \begin{bmatrix} \cos\psi\cos\theta & \sin\psi\cos\theta & -\sin\theta \\ -\sin\psi\cos\phi + \cos\psi\sin\theta\sin\phi & \cos\psi\cos\phi + \sin\psi\sin\theta\sin\phi & \cos\theta\sin\phi \\ \sin\psi\sin\phi + \cos\psi\sin\theta\cos\phi & -\cos\psi\sin\phi + \sin\psi\sin\theta\cos\phi & \cos\theta\cos\phi \end{bmatrix} \quad (2.8)$$

Extrinsic parameters are determined by camera position on the hub and must be recalibrated after each system installation and allignment.

### Intrinsic Parameters

Intrinsic parameter are related to the CCD array-objective lens system. There are six intrinsic parameters:

$f$: effective focal length, or CCD array to projective center distance,
$k_2$, $k_4$: lens distortion coefficients,
$s_x$: uncertainty scale factor for line scanning, due to TV camera scanning and acquisition timing error,
$(C_x, C_y)$: computer image coordinate.

Intrinsic parameters can be determined on the special calibration setup in the laboratory environments before TV camera installation on the hub. This delicate operation requires high accuracy and can be applied for each combination of the TV camera-objective lens used in the measurement system. $s_x$ factor for CCD camera working in synchronous mode with frame grabber is determined by CCD pixel geometry and can be determined only once for future using. Determination of the other intrinsic parameters are described in the subsequent sections.

### Two stage technique for measurement system identification

Measurement system identification can be divide in two stage:

1. Intrinsic parameters computing - performed on special calibration setup.

2. Extrinsic parameters computing - performed directly on the hub with auxiliary tools.

## Stage 1: Intrinsic parameters computing.

### TV camera calibration setup

In accordance with approach described in section "System identification" TV camera calibration setup was developed and calibration procedures for "Monocor" CCD camera with objective lens were conducted. Calibration setup layout is presented on Fig. 2.2. TV camera is attached to x-stage positioner having accuracy in x positioning better then 0.01 mm. Video signal is captured by DT2255 frame grabber installed in personal computer. X coordinate is measured by photo gage and special board in computer mainframe.

Point light source simulates retroreflector signal. Adjustable diaphragm installed before light source gives possibility to vary dimension of the light spot image on the CCD array. Appropriate signal level is installed by neutral filters placed before light source. All optical

components are installed on the common stable base. Distance between CCD camera and Point Light Source was chosen 1.28 meter. Data acquisition and processing was performed with special software described below.

This calibration setup gives possibility to evaluate distortion parameters of the objective lens, to calculate its effective focal length, and as a result to obtain direct calibration function of the photo detector consisting of objective lens and CCD array.

w
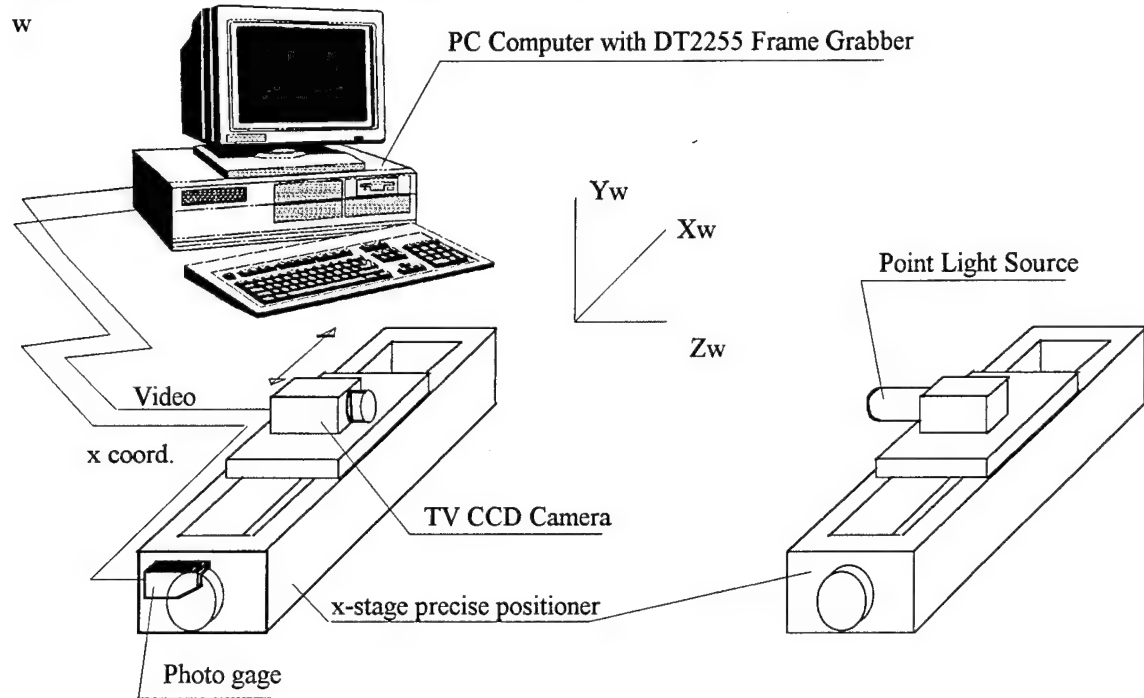


Fig. 2.2. Calibration setup.

*Software for the TV Camera Calibration Setup*

The software for the TV camera calibration facility consists of the two parts:

a) the software for frame grabber, produced by the "Data Translation" corporation;

b) the program for video signal processing and interpretation, produced by authors.

The MS DOS 6.2 operational system is used here. All programs are created with *ZORTECH C++ 3.1*. To provide the appropriate operation with Optical Table Facility, the programs for frame grabber are modified with *ZORTECH 3.1* as well.

The scheme at the picture shows the steps of video signal processing during the camera calibration.

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```
┌─────────────────────────────┐
│ TV monitor  TV camera       │
│                             │
│      Video Signal           │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐        ┌─────────────────────────────┐
│      Frame grabber          │        │        TV monitor           │
│    Digitized Image          │───────▶│                             │
│  DAC of Digitized Image     │        │                             │
└─────────────────────────────┘        └─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐        ┌─────────────────────────────┐
│     Host computer           │        │     Computer monitor        │
│     Preprocessing           │───────▶│     Input parameters        │
│                             │        │   Light spot coordinates    │
└─────────────────────────────┘        └─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│     Host computer           │
│     Post processing         │
│  Distortion coefficients    │
└─────────────────────────────┘
```
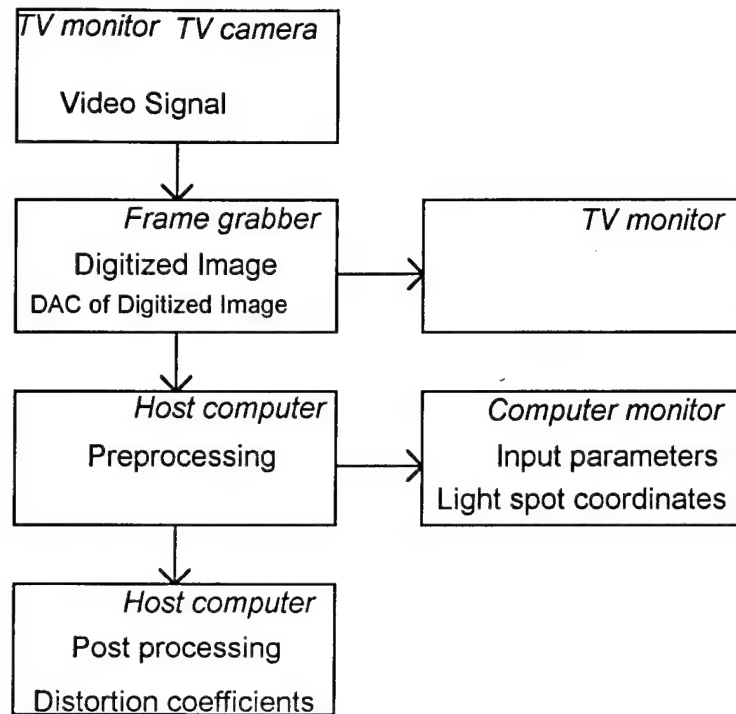
Fig. 2.3.

Let's consider the main steps of the software operation. The signal from TV camera is passed to frame grabber, which digitizes it and passes to TV monitor. It's the standard function of frame grabber software, modified by authors. The source of the optical signal is the laser focused to the some point. This point is moved with the aid of the micro coordinate system. The impulse counter shows the exact position of the light point in the space. The exact position of the light spot at the TV camera CCD array is calculated by the program which reads intensity of light from every pixel.. While the signal is processing the picture is freezing and the image of the light point appears at PC monitor. The angular coordinates of this point are the functions of the laser position. The second step of procedure is creation of the approximation polynomial, which is used for the experimental result processing.
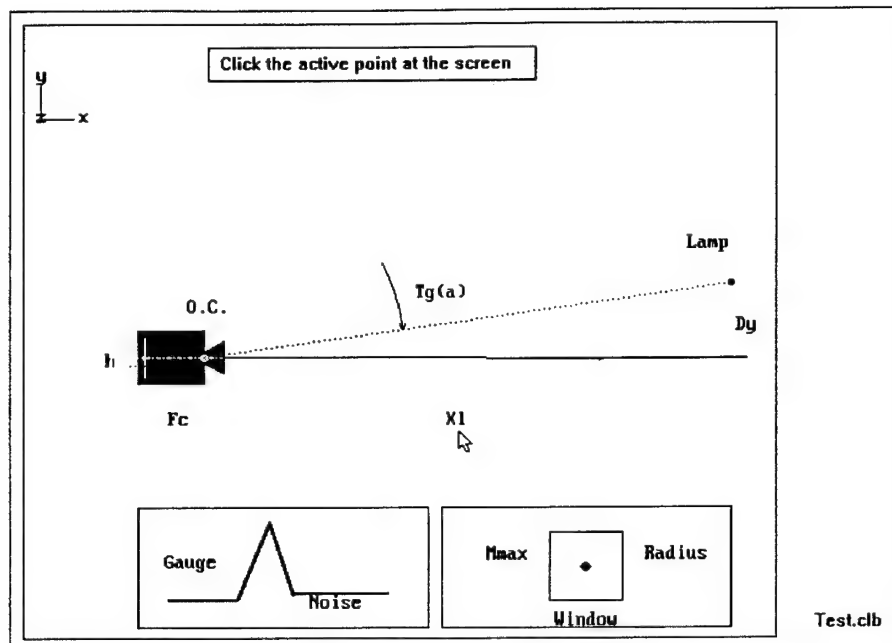
Fig. 2.4.

The scheme above shows the monitor screen image while the new parameters are choosing.

Gauge - threshold level
Noise - noise level
Window- window size
Radius - light spot size
Mmax - the number of light spots
    h      - the shift of the light spot
    Fc    - objective focus length
    Î.Ñ.  - optical center coordinates
    Xl    - the X coordinate of light point
    Dy   - the light point moving step
    Lamp  - the Y, Z coordinates of light spot

Any value from list above can be changed during the job.

- *Threshold level* determines the sensitivity of the system. If the signal is weaker than threshold, it isn't processing.
- *Noise level* determines the exactness of the system. If the signal is weaker than noise, it is supposed to be equal to zero. The noise level can't be more than threshold.
- *Window size* determines the domain at the TV camera active matrix which is used while the light spot is searching. Optimal window makes your job faster.
- *Light spot size* is used in the algorithm of the light point center coordinates calculation.
- *Number of light spots* shows the count of points for searching during one cycle.
- *Light spot shift* at the active matrix is used to calculate the angular coordinates of the light point - the main output parameter of the procedure.
- *Objective focus* is inputted and used for the light point angular coordinates calculation.
- *Optical center* coordinates are equal to zero in this version of the program.

- *X coordinate* of the light point is determined by the Calibration Facility configuration and is used for the point angular coordinates calculation.
- *Step* determines the count of Photo gage impulses, which are necessary for light point shifting. If step is equal to zero the manual procedure is used.
- *The initial coordinates Y, Z* of the light point are determined from the Optical Table Facility configuration.

The following algorithms are used in these programs:
- searching of the light spot center
- polynomial creation for date approximation

Let's consider this subject. The algorithm for the light spot center searching consists of the two steps: 1) the spot capture; 2) calculation of the spot center. The capture of the light spot is made inside of the definite window by the searching of the pixel with maximum intensity. The center of the spot is supposed to be the center of the weight of the appropriate figure restricted by the circle with definite radius.

The polynomial for the experimental date approximation is created with the aid of Least Square Approximation method. It is the last step of the calibration procedure. The function of the x-coordinate $X_w$ is approximated by formula

$$X_w = a_0 + a_1 \times x + a_2 \times x^2 + a_3 \times x^3 + a_4 \times x^4 + a_5 \times x^5$$

which is used to calculate distortion coefficients of objective lens installed on TV camera.

The menu system of calibration program permits you to make the next job:
- initiate the TV camera
- install the system parameters
- prescribe Nulls
- auto registration of all parameters
- create the polynomial
- save the information at hard disk
- continue the job after termination

The program contains the verification system, which permits to control the actions of the operator. It violates:

- to work without frame grabber initiation
- to work without light spot capture
- to work out the system restrictions

Results are presented like charts at the monitor screen. They can be saved in the TXT file, or tables.

### Calibration of the CCD camera "Monocor"

Calibration setup was used for investigating of the CCD camera "Monocor" used in laboratory measurement system. Plot on Fig. 2.5 illustrates distortion input in TV camera calibration:

$$d = X_w - a \times x - b,$$

where:

$X_w$ - x-coordinate in laboratory coordinate system, $[X_w]$=mm,

x - x-coordinate in CCD coordinate system, $[x]$=mm,

a,b - approximation coefficients for linear fitting.



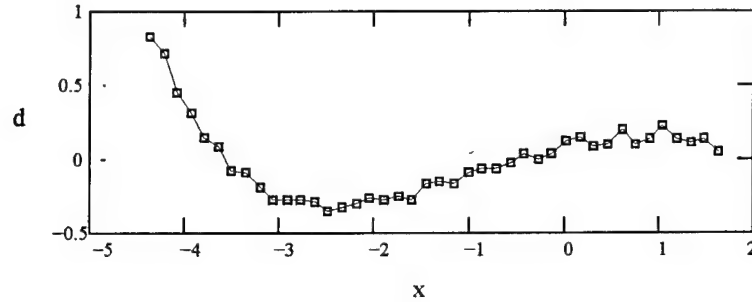Fig.2.5. Distortion input.

Polynomial approximation $qb(x)=a_0+a_1 \times x+a_2 \times x^2+a_3 \times x^3+a_4 \times x^4+a_5 \times x^5$, which can be rewritten in more suitable form:

$$X_w-X_{w0}=k_1 \times (x-x_0) \times [1+k_2 \times (x-x_0)^2+k_4*(x-x_0)^4],$$

gives estimation of the distortion coefficients $k_2=2.3031_{10}-4$, $k_4=8.061374_{10}-6$, scale coefficient $k_1=-81.87453$, coordinate offsets $X_{w0}=-0.11242$ mm, $x_0=-7.84897_{10}-7$ mm. Approximation error is 0.0351 mm, that corresponds to positioning error of x-stage. Approximation residues are presented on Fig. 2.6. Further increasing of the approximation degree doesn't give reliable results at least for 16 mm objective lens. Accuracy obtained on this calibration setup is enough for subsequent system extrinsic parameters identification.
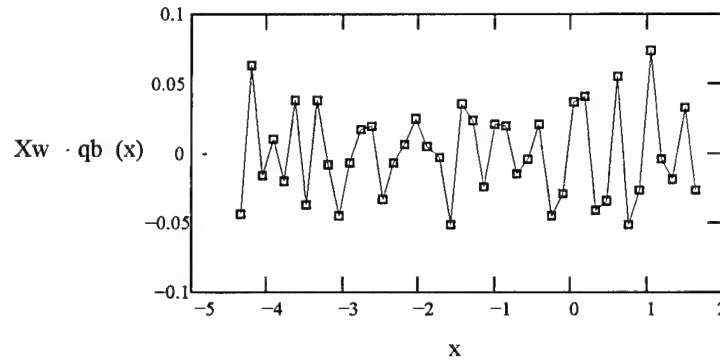


Fig. 2.6. Approximation residues.

## *Stage 2. :Computing of 3D orientation and position.*

In order to obtain information about camera orientation and position it is necessary to install some reference object before TV camera as shown on Fig. 2.7 Coordinates $(x_{hi}, y_{hi}, z_{hi})$ the marker points on the reference object are known in the hub coordinate system and are computed in image plane.
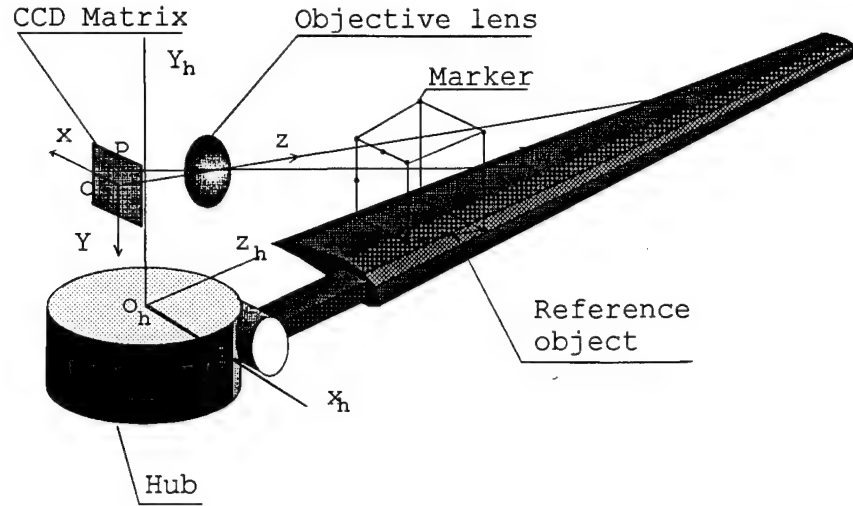
23

Fig. 2.7. Auxiliary reference object

As far as distortion coefficients and center pixel of frame memory are known it is possible to rewrite equations (2.7) for each marker point with $(x_{hi}, y_{hi}, z_{hi})$ as 3D hub coordinate, and $(X_{di}, Y_{di})$ as image coordinate in the next form:

$$
X_{di} = f \frac{r_1 x_{hi} + r_2 y_{hi} + r_3 z_{hi} + T_x}{r_7 x_{hi} + r_8 y_{hi} + r_9 z_{hi} + T_z}
$$
$$
Y_{di} = f \frac{r_4 x_{hi} + r_5 y_{hi} + r_6 z_{hi} + T_y}{r_7 x_{hi} + r_8 y_{hi} + r_9 z_{hi} + T_z}
$$

(2.9)

which can set up the following linear equations with $(T_y^{-1} r_1, T_y^{-1} r_2, T_y^{-1} r_3, T_y^{-1} r_5, T_y^{-1} r_6, T_y^{-1} T_x)$ as unknowns:

$$
\begin{bmatrix} Y_{di} x_{hi} & Y_{di} y_{hi} & Y_{di} z_{hi} & Y_{di} & -X_{di} x_{hi} & -X_{di} y_{hi} & Y_{di} z_{hi} \end{bmatrix}
\begin{bmatrix} T_y^{-1} r_1 \\ T_y^{-1} r_2 \\ T_y^{-1} r_3 \\ T_y^{-1} T_x \\ T_y^{-1} r_4 \\ T_y^{-1} r_5 \\ T_y^{-1} r_6 \end{bmatrix} = X_{hi}
$$

(2.10)

With N (number of marker points) much larger than seven, an overdetermined system of linear equations can be established and solved for seven unknowns

$$
(T_y^{-1} r_1, T_y^{-1} r_2, T_y^{-1} r_3, T_y^{-1} r_4, T_y^{-1} r_5, T_y^{-1} r_6, T_y^{-1} T_x)
$$

(2.11)

Let $a_j, j = 1, \dots 7$ be defined as

$$
a_1 = T_y^{-1} r_1, a_2 = T_y^{-1} r_2, a_3 = T_y^{-1} r_3, a_5 = T_y^{-1} r_4, a_6 = T_y^{-1} r_5, a_7 = T_y^{-1} r_6, a_4 = T_y^{-1} T_x
$$

(2.12)

Module of $T_y$ is computed using the following formula:

$$
\left| T_y \right| = (a_5^2 + a_6^2 + a_7^2)^{-1/2}
$$

(2.13)

The sign of $T_y$ can be determined from the actual camera position in the hub coordinate system.

Calculated $T_y$ and solution of equations (2.10) gives $r_j$ ($j=1,\dots.6$) and $T_x$. Elements of the third row of rotation matrix $R$ can be computed as cross-product of the first two rows, using the orthonormal property of $R$ ($\|R\| = $ ).

For each marker, using known $Y_i$, $r_j$, $T_y$ and $T_x$, the following linear equation with unknown $f$ and $T_z$ can be established:

$$\left[\widetilde{Y}_i,-Y_i\right]\begin{bmatrix} f \\ T_z \end{bmatrix} = W_i Y_i \qquad (2.14)$$

where

$$\widetilde{Y}_i = r_4 x_{hi} + r_5 y_{hi} + r_6 z_{hi} + T_y$$

$$W_i = r_7 x_{hi} + r_8 y_{hi} + r_9 z_{hi}$$

With N marker points, this yields an overdetermined system of linear equations that can be solved for the unknowns effective focal length $f$ and $T_z$. Really for objective lens having $f \leq 16..20$ mm and $T_z > 1000$ mm it is possible to use value for $f$ obtained by camera calibration, but in general it is necessary to take into account some variation in effective focal length due to objective lens focusing.

All these steps were realized in computer program written on C language for DOS and "Windows" environments. Programs had numerous applications in image processing for Pressure Sensitive Paint technology. Practically the main difficulty is exact positioning of the reference object in the hub coordinate system.

# 3. Measurements of the wing model deformations.

Methodology described in the report was used in the investigations of the wing model tested in the wind tunnel. Due to large aerodynamic loads the wing suffered bending and torsion deformations. Schematic view on the experimental setup is presented on Fig. 3.1. The main experimental task was to evaluate deformations of a flap relative the wing body. The wing span was about 2.75 m and the flap was attached to the wing by the consoles. Our region of interest was central section of the wing between two pillars.
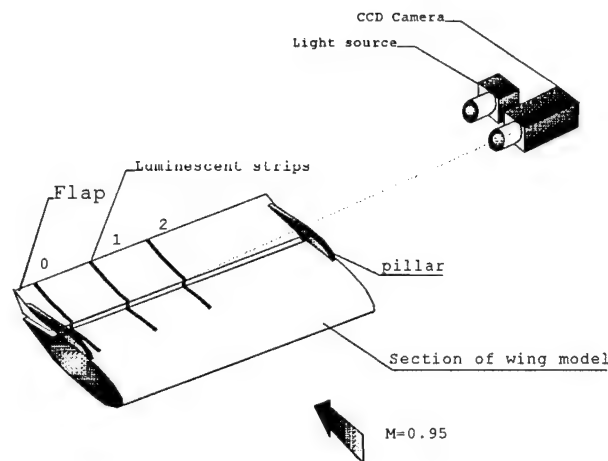


Fig. 3.1. Test schematics.

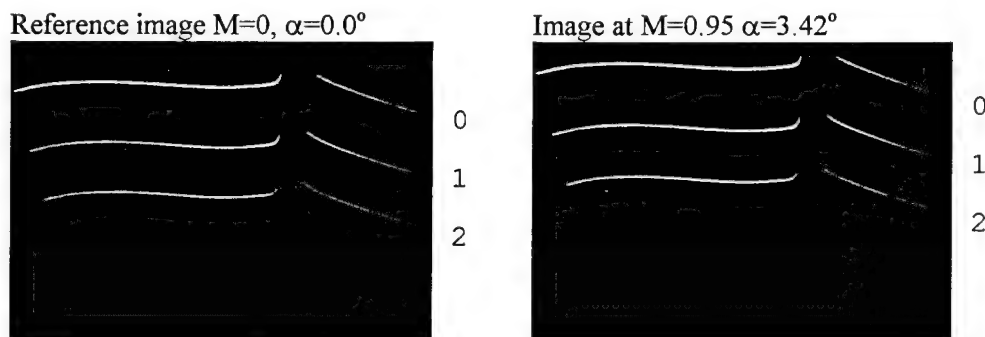Reference image M=0, α=0.0°          Image at M=0.95 α=3.42°



Fig. 3.2.

The maximum deformations were predicted in the central zone of the wing. Wing deformations and relative flap deformations significantly modify the flow pattern and local loads' distribution. Three luminescent strips were glued to the model surface: one in the center of the section-marked "0", one near the console-"2", and one between them-"1". Nitrogen laser was used as a light source. CCD camera has 50 mm objective lens. Video signal was acquired by image processing system PC3000. One reference image (Fig. 3.2) was acquired before run and set of the images were acquired at different angles of attack (example on Fig. 3.2). CCD camera was installed on the wing support unit that significantly simplified the data processing and enlarged the spatial resolution. Direct camera calibration was used in these tests. It means that in each section was placed vertical rule having the set of luminescent strips with known step -- 5 mm in this case.

These images were acquired and processed. The set of the scale coefficients was computed and used in subsequent measurements.

Image processing consists of image scanning in vertical direction column by column and searching of linear "mass center" of the each strip image. The sets of these data are presented on the plot (Fig. 3.3). Linear displacements are the results of appropriate coordinate extraction. Measurements were concentrated on flap deformation investigation- in order to obtain maximum spatial resolution camera view field was restricted by flap region and strip length on the wing body was too small to resolve wing torsion. Wing body deformation as functions of the angle of attack are presented on Fig. 3.4. Linear least square approximation of flap section displacements gives flap torsion (Fig. 3.5) and flap displacements relative wing body (plot on Fig. 3.6).

These tests demonstrate the feasibility of the high resolution remote measurements in the wind tunnel environments
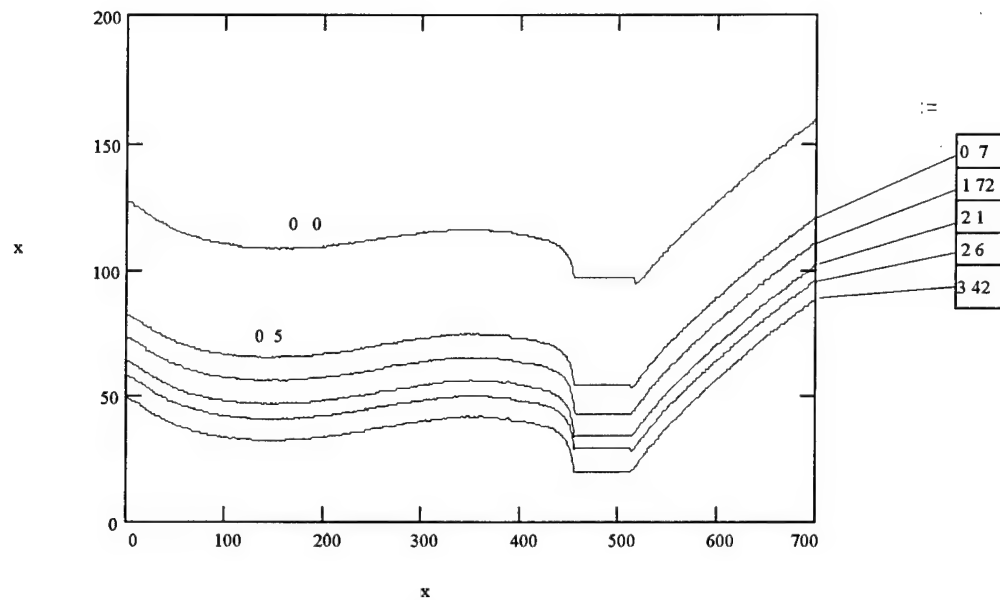


· Fig. 3.3. Mass "center" distributions as function of angle of attack $\alpha$ ([$\alpha$]= grad)
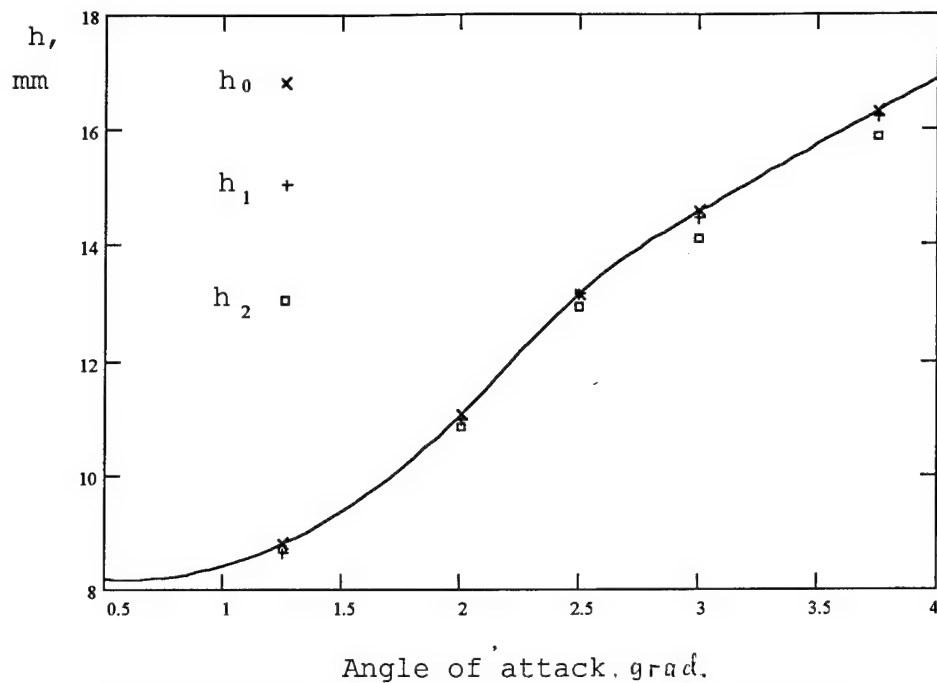
Fig. 3.4. Wing deformations for section "0" ($h_0$), "1" ($h_1$), "2" ($h_2$)



angle of attack, grad.
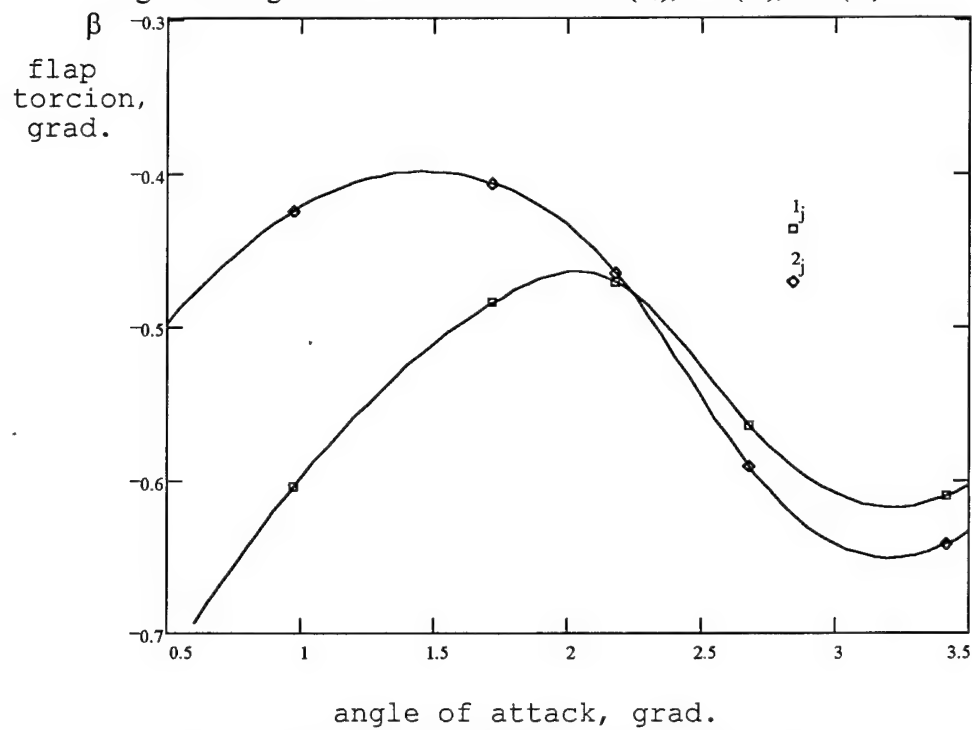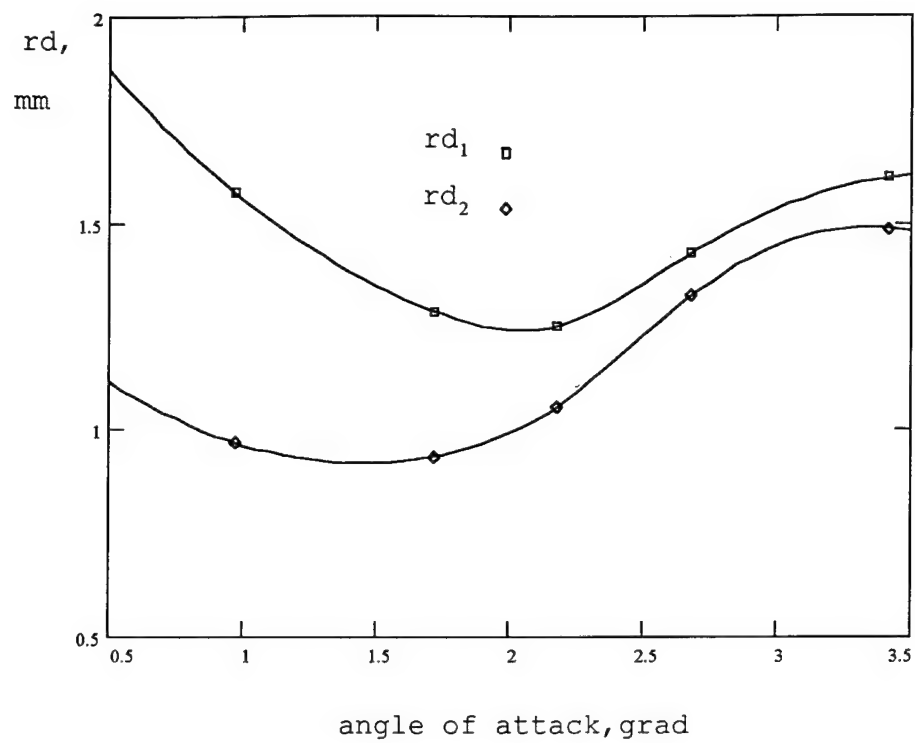Fig. 3.5. Flap torsion for section "1" and "2" (M=0.95)

Fig. 3.6. Flap relative displacements for sections "1" and "2" (M=0.95)

## 4. Conclusion.

Preliminary design stage of the project was accomplished in TsAGI in accordance with contract N 68171-94-C-9137. The main goals of this contract were:

1. to evaluate the possibility of the measurements,
2. to approve required measurement accuracy,
3. to develop measurement methodology,
4. to formulate the technical requirements to the prototype measurement system.

All investigations were carried out on the laboratory measurement system simulating real geometry and deformation of the rotor blade. Main results of these investigations are presented in the report.

1. Laboratory measurement system, including TV camera calibration setup was developed, aligned and tested.
2. The estimations show that geometry and optical parameters of the system are able to provide measurement of the cone flapping angle in the range -5 to 9 degrees. Measurement error is predicted to be not more then 1.5 mm for linear displacements of the blade end (L=8 m ) and 10 minutes for angle displacements.
3. Mean squared deviation obtained in experimental investigations is 0.2-0.6 mm for linear displacements and 1.-4.2 minutes for angular displacements.

4. Technical specification (Appendix 1) for prototype measurement system was developed and discussed.

5. Technical problems were discussed with US Army and NASA personnel at NASA Ames Research Center on 13-15 March 1994 and both sides were agreed that the work should continue toward providing an operational system for measuring rotor blade deflections in NFAC.

## TECHNICAL SPECIFICATION

### *for prototype measurement system.*

### *Purpose.*

Measurement system is aimed for non-invasive measurements of the dynamic deflection of large scale rotor blades during wind tunnel test.
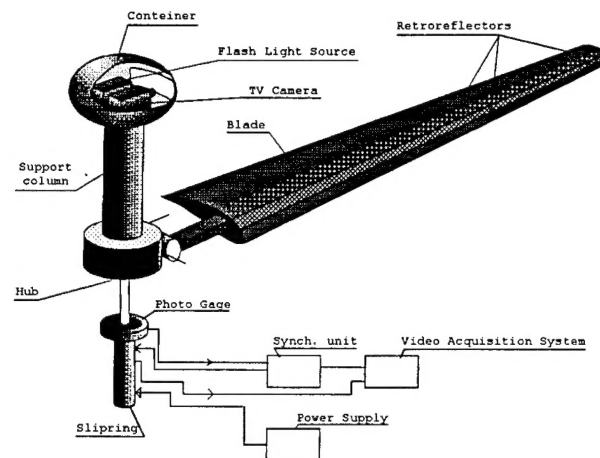


Fig. A1.1 General layout of the Prototype Measurement System

### *Requirements.*

1. The instrument package (Fig. A1.1) consists of:
    mast mounted optical head assembly

    data acquisition computer system, including frame grabber, synchronizing unit and computer platform,

    calibration facilities and units,

    special software.

2. Blade deflection measurements shall be performed for rotor having diameter up to 10-17 m in the next conditions:
    rotation speed from 200 to 600 RPM,
    rotor angle of attack -30-+30°,
    flow velocity 0-150 m/sec,
    dynamic pressure up to 2000 KPa.

3. Measurements shall be possible at 10 normalized span-wise (r/R) locations from 0.25 to 1.0 on the blade with span twist from 0 to 35°.

4. Measurement range refereed to the displacement of the blade tip:
    - 1000-+1500 mm in normal direction,
    - -700-+700 mm in lead-lag motions.

5. Maximum measurement rate up to 60 Hz.
    The frame acquisition timing must be synched to the rotor angular position. Phototach (provided by NASA) must provide 1/rev and 2048/rev TTL signals. These signals will be processed by custom timing electronics (provided by TsAGI) to drive TV camera vertical and

horizontal synch signals to provide a selectable integer number of samples per rotor revolution, up to a maximum of 60 Hz.

6. Absolute measurement error for linear displacement measurement (referred to the blade tip)-1.5 mm

7. Absolute measurement error for angular displacement measurements-10′

8. Optical recording unit of the system is placed on the rotor hub and attached to adapters using for RMDAS data system. Maximum mass and height of the optical recording unit shall not exceed 20 kg and 0.5 m accordingly.
   Number of slipring used for energy and data transfer is ten with maximum current limitation of 3 amps for four channels.

9. Optical recording unit shall be balanced with accuracy 2g∗cm and shall withstand to the vibrator loads up to +/-0.5 G and shock loads up to +/-12 G.

10. TV components (CCD camera and frame grabber) shall be in RS170 standard. Spatial resolution for TV camera and frame grabber (provided by NASA) shall be 512 by 512 pixels. Frame buffer, installed in the grabber or mapped directly in a host computer memory must be able to store at least 16 frames with 512×512×8 bits resolution. TV camera and frame grabber must have possibilities to work in asynchronous mode.

11. Electronic components of the system shall have US identical item.

12. Software package shall provide the next properties:
    · System control in automatic and manual mode,
    · System calibration,
    · Data acquisition, storage and preliminary processing,
    · Data post processing and data presentation,
    · Experimental Data Base support.

13. Software package shall operate in "Windows" environments

14. Software is supplied as source C-code, libraries and executable modules.

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